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16. ABSTRACT

This paper describes the current state of EPA's Complex Terrain Dispersion Model (CTDM), which has been under development during the past five years. The CTDM employs the concept of a dividing streamline height (a function of wind and temperature profiles), below which plume segments pass round the sides of a hill and/or above which they pass up and over the top. The model is currently constrained to simulate concentrations on the windward side of isolated terrain. The paper includes a comparison of CTDM concentration estimates with concentrations observed during a recent tracer study from a power plant in the Sierra-Nevada Mountains. Most of the time-paired comparisons are within a factor of two, but there is a trend to underestimate the larger observed concentrations.

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INTRODUCTION

The goal of the current phase of the EPA Complex Terrain Model Development (CTMD) project is to develop, evaluate, and refine atmospheric dispersion model(s) to calculate hourly ground-level concentrations in hilly or mountainous terrain during stable conditions, i.e., to handle the stable plume impingement problem. The initial version of the Complex Terrain Dispersion Model (CTDM) developed under this program is based on (1) theoretical work on stable flows in complex terrain; (2) tracer studies conducted at Cinder Cone Butte (CCB), the Hogback Ridge (HBR) and, to some extent, the Full Scale Plume Study (FSPS) at the Tracy Power Plant; and (3) tow tank and wind tunnel studies performed at the EPA Fluid Modeling Facility (FMF). While the concepts inherent in the model are considered generally applicable, this version is designed to simulate concentrations over the windward side of isolated hills or hill segments. A full description of CTDM is contained in the 4th and 5th project milestone reports[1,2].

This paper presents a brief description of CTDM, the FSPS, and some initial tests of the model on a portion of the FSPS dataset.

TECHNICAL BASIS FOR THE COMPLEX TERRAIN DISPERSION MODEL

CTDM is a point source plume model which incorporates several concepts about stratified flow and dispersion over an isolated hill or separable hill segment. A central feature of CTDM is its use of a critical dividing-streamline height (H_c) to separate the flow into two discrete layers. This basic concept was suggested by theoretical arguments of Drazin[3] and Sheppard[4] and was demonstrated through laboratory experiments by Riley et al.[5], Brighton[6], Hunt and Snyder[7], Snyder et al.[8], and Snyder and Hunt[9]. In the layer above H_c, the approach flow has sufficient kinetic energy to transport a fluid parcel up and over the hill, against the density gradient of the ambient stratification. In the layer below H_c, the approach flow has insufficient kinetic energy to "push" the parcel over the hill, so that the flow below H_c is restricted to lie in a nearly horizontal plane, allowing little motion in the vertical. Consequently, plume material below H_c travels along and around the terrain, rather than up and over the terrain. In practice, H_c can be computed from profiles of wind speed and temperature by locating the height at which the kinetic energy of the approach flow just balances the potential energy attained by elevating a fluid parcel from this height to the top of the hill.

Two separate components of CTDM compute ground-level concentrations resulting from material in each of these flows. LIFT handles the flow above H_c, and WRAP handles the flow below H_c.

The LIFT Component

The flow above H_c is considered to be weakly stratified. That is, the stratification is strong enough to influence the flow pattern (e.g., lee

waves), but not strong enough to inhibit significant vertical motion. To simplify the modeling task, H_c is assumed to be a level surface, and the flow above H_c only "sees" that portion of the hill that lies above H_c.

The plume is allowed to develop as if the terrain were flat until it reaches the point where its trajectory crosses the height contour equal to H_c in elevation (say, at a distance s_o from the source, see Figure 1). Beyond s_o, the plume material below H_c is disregarded by the LIFT component, and the evolution of the remaining material is modeled as if the terrain were flat, and the lower boundary were H_c (with full reflection). However, the wind speed, the height of plume material above H_c, plume spread, and lateral position of the plume centerline relative to the receptor are all modified to reflect the net alteration of these properties between s_o and s (where s is the distance from the source to the receptor) induced by the presence of the hill. The simplicity of the Gaussian plume solution is retained in this way, while the full dilution of the plume from the source to the hill (s_o) as well as the effects of the hill on both flow and dispersion beyond s_o are explicitly incorporated.

Terrain-induced modifications to the plume arise from the distortion of the flow over the hill. Adjacent streamlines are deflected by differing amounts, which in turn changes the spacing between streamlines and hence, causes changes in the local speed of the flow. As a result, the plume trajectory is curved, the plume distorts so that it is thinner in the vertical direction and wider in the lateral direction, the turbulence statistics vary, and as shown in Hunt and Mulhearn[10], turbulent diffusion across streamlines is enhanced by the contraction in the distance between streamlines in the vertical direction, and retarded by the expansion in the distance between streamlines in the lateral direction.

The concentration at a receptor downwind of s_o is composed of contributions from the entire concentration distribution at s_o. Conceptually, the flux of plume material through the plane at s_o can be thought of as a distribution of point sources. If we track the plume material in terms of distance, s, downwind of the source then the source strength of one of these point source elements located at the point (s_o,y,z) is given by:

$$dQ(s_o,y,z) = C(s_o,y,z)u\ dy\ dz \tag{1}$$

Because the flow beyond s_o is taken to be uniform, the influence of each of these sources follows the Gaussian plume solution to the advective diffusion equation so that the contribution of the source element at the point (s_o,y,z) to the concentration at the point (s,l,h) is:

$$dC(s,l,h;s_o) = \frac{dQ(s_o,y,z)}{2\pi\sigma_y^*\sigma_z^* u}\ e^{-0.5\left(\frac{y-l}{\sigma_y^*}\right)^2}\ \left[e^{-0.5\left(\frac{z-h}{\sigma_z^*}\right)^2} + e^{-0.5\left(\frac{z+h}{\sigma_z^*}\right)^2}\right] \tag{2}$$

where σ_y^*, σ_z^* denote the plume spread statistics for each point source element

over the interval $s-s_o$. The total concentration at (s,l,h) is found by integrating Equation 2 over all point source elements, so that

$$C(s,l,h;s_o) = \int_0^{\infty}\int_{-\infty}^{+\infty} \frac{C(s_o,y,z)}{2\pi\sigma_y^*\sigma_z^*} e^{-0.5\left(\frac{y-l}{\sigma_y^*}\right)^2} \left(e^{-0.5\left(\frac{z-h}{\sigma_z^*}\right)^2} + e^{-0.5\left(\frac{z+h}{\sigma_z^*}\right)^2}\right) dy\,dz \qquad (3)$$

The plume spread statistics σ_y^* and σ_z^* for the interval $s-s_o$ are specified by the requirement that Equation 3 for flat terrain reduces to the expression obtained for the original point source located at $s = 0$ (i.e., Equation 2 with $s_o = 0$ and $\sigma^* = \sigma(s)$). Equating these two expressions for C,

$$\sigma^{*2} = \sigma^2(s) - \sigma^2(s_o) \qquad \text{(denoted as } \sigma^2 - \sigma_o{}^2) \qquad (4)$$

Terrain influences are incorporated by <u>deforming</u> the source distribution at s_o (Equation 1), and by <u>altering</u> the flow in which the source elements diffuse. For a receptor located at (s,y_R) on the <u>surface</u> of a hill ($h = 0$), the concentration due to one elemental point source is obtained at $(s,y_R,0)$ through Equation 2 by replacing $y,z,\sigma_y^*,\sigma_z^*$, and u with y', z', $\sigma_y^{*\prime}$, $\sigma_z^{*\prime}$, and u' to simulate the average change in these properties over the interval $s-s_o$ caused by the influence of the terrain; and by introducing H_c' as the lower boundary--the effective hill surface. With these substitutions, Equation 2 becomes

$$dC(s,y_R,0;s_o) = \frac{dQ(s_o,y',z')}{\pi\sigma_y^{*\prime}\sigma_z^{*\prime}u'} e^{-0.5\left(\frac{y'-y_R}{\sigma_y^{*\prime}}\right)^2} e^{-0.5\left(\frac{z'-H_c'}{\sigma_z^{*\prime}}\right)^2} \qquad (5)$$

The total concentration contains contributions only from those source elements above H_c', so that Equation 3 becomes

$$C(s,y_R,0,s_o) = \int_{H_c'}^{\infty}\int_{-\infty}^{+\infty} \frac{C(s_o,y',z')}{\pi\sigma_y^{*\prime}\sigma_z^{*\prime}} e^{-0.5\left(\frac{y'-y_R}{\sigma_y^{*\prime}}\right)^2} e^{-0.5\left(\frac{z'-H_c'}{\sigma_z^{*\prime}}\right)^2} dy'dz' \qquad (6)$$

where

$$C(s_o,y',z') = \frac{Q}{2\pi u'\sigma_{yo}\sigma_{zo}} e^{-0.5\left(\frac{y'-y_r'}{\sigma_{yo}}\right)^2} \left[e^{-0.5\left(\frac{z'-z_r'}{\sigma_{zo}}\right)^2} + e^{-0.5\left(\frac{z'+z_r'}{\sigma_{zo}}\right)^2}\right] \qquad (7)$$

Note that the plume is originally released at the point (x_r,y_r,z_r). After the deformation at the distance s_o, the plume centerline passes through the point (s_o,y_r',z_r').

Primed quantities in Equations 6 and 7 are related to the unprimed quantities of the undistorted flow by means of terrain factors (see Figure 2). These factors are local in the sense that they depend on the position of the receptor on the terrain and the height of the plume in the approach flow. They represent the average terrain effect on the flow from s_o to s. T_h and T_l are

factors that specify the amount of streamline distortion in the vertical and lateral directions, and T_u specifies the resultant change in the flow speed.

The factor T_σ (denoting either $T_{\sigma z}$ or $T_{\sigma y}$) should account for the effective growth of the plume element in the altered flow between s and s_o and can be expressed in terms of the diffusivity. The diffusivity over the interval $s-s_o$ can be related to the growth of a plume element in the following way. Assume that the hill-slope is small enough that the time-of-travel effects can be ignored, then:

$$\frac{d}{dt}\,\sigma^2(t) = 2K(t) \tag{8}$$

Denote a mean diffusivity over the interval $s-s_o$ (or $t-t_o$) by K_m, then

$$\sigma^{*2} = \sigma^2 - \sigma_o^2 = \frac{\Delta\sigma^2}{\Delta t}\,(t-t_o) = 2K_m\,(t-t_o) \tag{9}$$

Therefore T_σ, the factor that relates the growth of the terrain-influenced plume element $\sigma^{*\prime}$ to the uninfluenced growth σ^*, is evaluated from

$$T_\sigma^2 = \sigma^{*\prime 2}/\sigma^{*2} = K_m'/K_m \tag{10}$$

With these terrain factors, the explicit relationship between the initial plume and the distorted plume is given by the following:

$$z_r' = T_h z_r \qquad H_c' = T_h H_c \qquad y_r' = T_l y_r \qquad u' = T_u u \tag{11a}$$

$$\sigma_z'^2 = T_h^2\sigma_{zo}^2 + T_{\sigma z}^2\sigma_z^{*2} = T_h^2\sigma_{ze}^2$$

$$\sigma_y'^2 = T_l^2\sigma_{yo}^2 + T_{\sigma y}^2\sigma_y^{*2} = T_l^2\sigma_{ye}^2 \tag{11b}$$

Equations 11b define the effective sigmas:

$$\sigma_{ze}^2 = \sigma_{zo}^2 + \sigma_z^{*2}/T_z^2 \qquad \sigma_{ye}^2 = \sigma_{yo}^2 + \sigma_y^{*2}/T_y^2 \tag{11c}$$

where $T_z = T_h/T_{\sigma z}$ and $T_y = T_l/T_{\sigma y}$.*

Upon solving the integrals in Equation 6 and substituting Equations 11 for the primed quantities, the resulting expression for the concentration is

$$C(s,y_R,0;s_o) = \frac{Q\,e^{-0.5\left(\frac{y_R/T_l - y_r}{\sigma_{ye}}\right)^2}}{2\pi\sigma_{ye}\sigma_{ze}u}\left\{e^{-0.5\left(\frac{z_r-H_c}{\sigma_{ze}}\right)^2}\operatorname{erfc}\left[\sigma_z^*(H_c-z_r)/T_z\sigma_{ze}\sigma_{zo}\sqrt{2}\right]\right.$$

$$\left. + \; e^{-0.5\left(\frac{z_r+H_c}{\sigma_{ze}}\right)^2}\operatorname{erfc}\left[\sigma_z^*(H_c+z_r)/T_z\sigma_{ze}\sigma_{zo}\sqrt{2}\right]\right\} \tag{12}$$

Terrain-induced modifications are easier to observe if H_c is set to zero:

$$C(s,y_R,\emptyset;s_o) = \frac{Qe^{-\emptyset.5(y_R/T_1-y_r)^2/\sigma_{ye}}}{\pi\sigma_{ye}\sigma_{ze}u} e^{-\emptyset.5(z_r/\sigma_{ze})^2} \quad (13)$$

Equation 13 differs from the simple flat terrain Gaussian plume equation only in the appearance of a distortion factor T_1 in the lateral distribution term and in the appearance of effective plume spread parameters. Aside from the lateral shift in the impact region on the terrain, the influence of the terrain is exhibited only through changes in the rate of effective plume growth. When T_z is less than unity (this is generally the case), σ_{ze} exceeds σ_z at s and thus more plume material may lie "nearer" the surface. As a consequence, Equation 12 may estimate ground-level concentrations in excess of flat terrain estimates even when H_c is zero.

If H_c is non-zero but less than z_r, Equation 12 will estimate even greater ground-level concentrations because the flow in the layer from the surface to H_c is "removed", allowing the less dilute portion of the plume to approach nearer the surface (see Figure 2). In particular, if $H_c = z_r$, then Equation 12 places the centerline concentration at ground level, an "impingement" result.

The WRAP Component

A particle in a steady two-dimensional flow around an object will experience both accelerations and decelerations. The magnitude of these changes in speed depends upon how close the particle is to the stagnation streamline of the flow. Maximum changes occur for particles on the stagnation streamline. Furthermore, the spacing between adjacent streamlines varies in inverse proportion to these changes in the speed along streamlines.

Two key approximations in the WRAP component are (1) lateral diffusion is insensitive to accelerations in the flow (i.e., the kinematic deformation of the plume has no effect on the diffusion rate), and (2) vertical diffusion increases with increases in travel-time caused by terrain-induced alterations in the flow speed. Furthermore, the mean flow for the averaging period (one hour) is considered steady, while all of the variability in the flow over the period, including that due to meandering, is considered "turbulence".

The influence of the terrain is modeled in WRAP by re-initializing the flow at the distance s_o downwind of the source (see Figure 1). The concentration at a receptor downwind of s_o is composed of concentrations from that part of the concentration distribution at s_o that lies below H_c, and that also lies on the same side of the stagnation streamline as the receptor (see Figure 1). Reflection of plume material in the vertical is allowed from the plane $z = \emptyset$ over the entire distance s, and reflection in the horizontal is

also allowed from the hillside beyond s_o. Note that the stagnation streamline forms the boundary of the hill surface in horizontal cross section.

For a receptor located on the hillside at a distance s and a height z_R above the plane z = 0, the concentration due to one elemental point source located at (s_o,y,z) in the plume is given by

$$dC(s,0,z_R;s_o) = \frac{dQ(s_o,y,z)}{2\pi u\sigma_y^*\sigma_z^*} \; 2e^{-0.5(\frac{y}{\sigma_y^*})^2} \; (e^{-0.5(\frac{z-z_R}{\sigma_z^*})^2} + e^{-0.5(\frac{z+z_R}{\sigma_z^*})^2}) \qquad (14)$$

The total concentration at the receptor contains contributions from those elements below H_c and on the same side of the stagnation streamline as y_r:

$$C(s,0,z_R;s_o) = \int_0^{H_c}\int_{(o)}^{(\infty)} \frac{C(s_o,y,z)}{2\pi\sigma_y^*\sigma_z^*} \; 2e^{-0.5(\frac{y}{\sigma_y^*})^2} \; (e^{-0.5(\frac{z-z_R}{\sigma_z^*})^2} + e^{-0.5(\frac{z+z_R}{\sigma_z^*})^2}) dydz \qquad (15)$$

where

$$C(s_o,y,z) = \frac{Q}{2\pi u\sigma_{yo}\sigma_{zo}} \; e^{-0.5(\frac{y-y_r}{\sigma_{yo}})^2} \; (e^{-0.5(\frac{z-z_r}{\sigma_{zo}})^2} + e^{-0.5(\frac{z+z_r}{\sigma_{zo}})^2}) \qquad (16)$$

These expressions are analogous to Equations 5 through 7 of the LIFT component. The integral for dy has the limits (o) and (∞). This is meant to denote integrating from 0 to +∞ if the receptor lies on the "positive" side of the stagnation streamline, and integrating from −∞ to 0 if the receptor lies on the "negative" side. Note that material is allowed to diffuse upwards through H_c so that receptors which lie above H_c, and which are downwind of s_o, can receive a contribution from the elemental point-sources below H_c. The total concentration at such receptors is the sum of both the LIFT and WRAP contributions.

The integrals in Equation 15 are evaluated to obtain:

$$C(s,0,z_R;s_o) = \frac{Q}{4\pi u\sigma_y\sigma_z} \; e^{-0.5(\frac{d}{\sigma_y})^2} \; \{1+\text{sign}(y_R)\,\text{erf}[\sigma_y^* d/(\sqrt{2}\sigma_{yo}\sigma_y)]\} \; \{B_1 \, e^{-0.5(\frac{z_r-z_R}{\sigma_z})^2} + B_2 \, e^{-0.5(\frac{z_r+z_R}{\sigma_z})^2}\} \qquad (17)$$

The factor $\text{sign}(y_R)$ denotes the sign of the receptor position in the coordinate system with x-axis aligned with the flow, and it results from the choice of integrating over the "positive" or "negative" portion of the flow in Equation 15. The factors B_1 and B_2 are given by

$$B_1 = \text{erf}(\frac{b_1-b_2-b_3}{b_o}) + \text{erf}(\frac{b_1+b_2+b_3}{b_o}) \qquad B_2 = \text{erf}(\frac{b_1-b_2+b_3}{b_o}) + \text{erf}(\frac{b_1+b_2-b_3}{b_o}) \qquad (18)$$

where

$$b_o = \sqrt{2}\sigma_z\sigma_{zo}\sigma_z^* \qquad b_1 = H_c\sigma_z^2 \qquad b_2 = z_R\sigma_{zo}^2 \qquad b_3 = z_r\sigma_z^{*2}$$

The subscript R denotes the receptor location, and the subscript r denotes the source location (see Figure 1). The distance from the stagnation streamline associated with the mean wind direction to the centerline of the plume is denoted as d, the total sigma-y (for horizontal spread of the mean plume) as σ_y, and the total sigma-z (for the vertical spread) as σ_z. The amount of plume spread experienced over the distance to the stagnation point is denoted as σ_{zo} and σ_{yo}, and the rate of plume growth beyond the stagnation point to the receptor is denoted as σ_z^* and σ_y^*, as in LIFT.

The size of the ellipse that is used to estimate the flow below H_c is taken from the horizontal cross-section of the hill at the minimum of the following two elevations: either the elevation of the centerline of the plume, or the elevation of H_c. In this way the scale of the hill selected is associated with the peak concentration of plume material found within the layer of fluid below H_c. As a consequence, the position of the impingement point (or the stagnation point) is also associated with the peak concentration of plume material below H_c.

Concentrations at receptors located on the hillside upwind of the stagnation point are estimated as if the receptor sits on a pole of height equal to the receptor elevation above the base of the stack. Furthermore, the lateral distance between the plume centerline and the receptor is set equal to d, so that concentrations at all of these receptors are controlled by the amount of material on the stagnation streamline. In this way plume material below H_c and below plume centerline height follows streamlines around the hill, and only material which diffuses onto the stagnation streamline impinges on the hill.

Dispersion Coefficients

The vertical and horizontal spread parameters σ_z and σ_y used in CTDM are appropriate for stable or near-neutral conditions. Both have the form

$$\sigma = i\ u\ t/(1+0.5t/t_L)^{\frac{1}{2}} \tag{19}$$

where i is the intensity of turbulence. For σ_y, the Lagrangian time scale t_L is estimated from turbulence measurements for 5-minute and 1-hour periods. In general, t_L is large enough that σ_y grows linearly with time. For σ_z, t_L is given by (Venkatram et al.[11])

$$\frac{1}{t_L} = \frac{\sigma_w}{\Gamma z} + \frac{N}{\gamma 2} \tag{20}$$

where Γ and γ^2 are approximately equal to 0.36 and 0.27, respectively and N is the Brunt-Vaisala frequency. Buoyancy-induced growth in σ_z is also included, and is implemented by means of a virtual source position.

THE FULL SCALE PLUME STUDY (FSPS)

The FSPS was conducted at the Tracy Power Plant near Reno, Nevada in August 1984. A detailed description of the FSPS is given by DiCristofaro et al.[2] The plant has three units of 53, 80 and 120 MW, although only the latter has been used recently. The 120-MW unit is serviced by a 91.3 m stack which was used to release the oil-fog and SF_6 tracer gas during the experiment. CF_3Br tracer gas was released from a 150-m meteorological tower located about 1.2 km east of the Tracy stack.

The power plant is located about 27 km east of Reno in the Truckee River Valley, a relatively narrow valley which is oriented east-west. Mountain peaks rise to elevations of 900 m above the base of the stack within 6.5 km of the plant. At about 4.5 km east of the plant, the river swings sharply north through a narrow gorge between two large terrain features, "Beacon Hill" (300 m above stack base) to the west of the gorge and "Target Mountain" (460 m above stack base) to the east. These two terrain elements were the principle "target" areas in the anticipated westerly winds.

The FSPS included tracer and flow visualization experiments with concurrent meteorological, lidar, and photographic measurements. One-hour samples of ground-level tracer concentrations were obtained at more than 100 locations. Three additional samplers were mounted on the 150-m tower. Meteorological measurements were made from the 150-m tower, four 10-m towers, two electronic weather stations, two tethersondes, and one monostatic and two doppler sodars. Two radar-tracking balloon sounding systems were also used. Ground-based lidar made vertical transects through the oil-fog plume to measure the location and dimensions of the plume and its proximity to terrain. The ALPHA-1 airborne lidar tracked the plume to greater distances. Color slides of the plume were taken routinely every five minutes from five locations, and video-tapes were made during the daylight hours.

The FSPS database contains 14 experiments and a total of 128 hours of data collection. The experiments encompass a variety of meteorological conditions ranging from very stable with very light winds to morning inversion breakup and fumigation. Prolonged periods of stable plume impaction on the targeted elevations to the east of the plant frequently occurred.

PRELIMINARY MODELING RESULTS

CTDM has been run for a subset of the SF_6 data base. Hours selected for modeling are those that contain a substantial plume impact on either Target Mountain or Beacon Hill. Each of these terrain features is modeled separately. In all, 39 hours are simulated for receptors on Beacon Hill, and 47 hours are simulated for receptors on Target Mountain.

Plume rise and the initial size of the plume are provided by the data obtained from the ground-based lidar. Hourly averaged meteorological data from the 150-m tower provide the means for calculating all of the other data needed in the model. Note, however, that wind speed and direction at elevations greater than 150 m are taken to be equal to those measured at 150 m, and the temperature gradient above 150 m is taken to be equal to the gradient measured between 125 m and 150 m.

Modeled concentrations are compared with observed concentrations after averaging the two greatest observed concentrations and the two greatest modeled concentrations for each hill and each hour simulated. Thus, the observed and modeled concentrations may not be paired in space, but they are paired in time for each hill. By averaging the top two concentrations for each hill and event, we seek to characterize the ability of CTDM to reproduce the mean concentration in the zone of greatest plume impact, rather than its ability to reproduce the peak concentration observed.

The upper portion of Figure 3 displays the results. Observed concentrations (scaled by emission rate) less than approximately 1 $\mu s/m^3$ tend to be modeled better than those greater than approximately 1 $\mu s/m^3$. Most of these smaller concentrations are estimated to within better than a factor of two. However, the greater observed concentrations tend to be underestimated by CTDM. One reason for this tendency for CTDM to underestimate concentrations at the FSPS was discussed at length in DiCristofaro et al.[2], and pertains to the σ_z estimates in stably stratified flow above a shallow surface layer. The σ_z expression (Equation 19) is directly proportional to i_z, and therefore σ_w as well. Measured values of σ_w in very stable conditions generally reflect a mix of turbulence and wave motions. Equation 19 assumes that the measured σ_w arises solely from turbulence. Consequently, the wave contribution to σ_w causes σ_z to be overestimated far from the source.

A revision to the use of σ_w data in CTDM is still under development, but an indication of its potential impact on model performance can be obtained by setting σ_w nearly equal to zero for a subset of the hours in which significant wave motion might be anticipated. For the sake of illustration in this paper, we choose to lump all hours in which the vector-averaged wind speed at plume height is less than 3 m/s into such a subset. The results are displayed in the lower portion of Figure 3 (labeled as Method 2). Fewer points now lie below the factor-of-two underestimation line, while more points lie above the factor-of-two overestimation line, and there is a notable improvement in the model performance in simulating the concentrations observed to be greater than approximately 2.5 $\mu s/m^3$.

The lack of a greater degree of improvement is not surprising: a simple wind speed indicator for "turning off" σ_w cannot be right. Also important are assumptions about the horizontal distribution of plume material, and time-of-travel considerations. The horizontal distribution of plume material was

frequently non-Gaussian under the lighter wind speeds observed, and the time-of-travel to Beacon Hill or Target Mountain was often the better part of an hour. These aspects of applying CTDM to the FSPS database are currently being explored.

CONCLUSIONS

An initial comparison of CTDM concentration estimates with those observed in the two primary impact areas (Beacon Hill and Target Mountain) of the FSPS database indicates that the model exhibits typical Gaussian plume performance in that most of the time-paired concentrations are within a factor of two. However, there is an unmistakable trend toward underestimating the larger observed concentrations.

Modifications to CTDM that are currently being developed appear to promise better model performance, especially in regard to decreasing the tendency toward underestimation.

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REFERENCES

1. D. Strimaitis, T. Lavery, A. Venkatram, D. DiCristofaro, B. Greene, B. Egan, EPA Complex Terrain Model Development Fourth Milestone Report - 1985, Report No. EPA/600/3-84/110, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1985, 319pp.

2. D. DiCristofaro, D. Strimaitis, B. Greene, R. Yamartino, A. Venkatram, D. Godden, T. Lavery, B. Egan, EPA Complex Terrain Model Development Fifth Milestone Report - 1985, Report No. EPA/600/3-85/069, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1986, 277pp.

3. P.G. Drazin, "On the steady flow of variable density past an obstacle, " Tellus 13: 239 (1961).

4. P.A. Sheppard, "Airflow over mountains," Quart. J. R. Meteor. Soc. 82: 528 (1956).

5. J.J. Riley, H.T. Liu, E.W. Geller, A Numerical and Experimental Study of Stably Stratified Flow Around Complex Terrain, Report No. EPA/600/4-76/021, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1976, 41pp.

6. P.W.M. Brighton, "Strongly stratified flow past three-dimensional obstacles," Quart.J.R. Meteor. Soc. 104: 289 (1978).

7. J.C.R. Hunt, W.H. Snyder, "Experiments on stably and neutrally stratified flow over a model three-dimensional hill," J. Fluid Mech. 96: 671 (1980).

8. W.H. Snyder, R.E. Britter, J.C.R. Hunt, "A fluid modeling study of the flow structure and plume impingement on a three-dimensional hill in stably stratified flow," Proc. Fifth Int. Conf. on Wind Engr. (J.E. Cermark, ed.), 1, Pergamon Press, New York, NY, 1980, 319pp.

9. W.H. Snyder, J.C.R. Hunt, "Turbulent diffusion from a point source in stratified and neutral flows around a three-dimensional hill; part-II laboratory measurement of surface concentrations," Atmos. Environ. 18: 1969 (1984).

10. J.C.R. Hunt, R.J. Mulhearn, "Turbulent dispersion from sources near two-dimensional obstacles," J. Fluid Mech. 61: 245 (1973).

11. A. Venkatram, D. Strimaitis, D. DiCristofaro, "A semi-empirical model to estimate vertical dispersion of elevated releases in the stable boundary layer," Atmos. Environ. 18: 923 (1984).

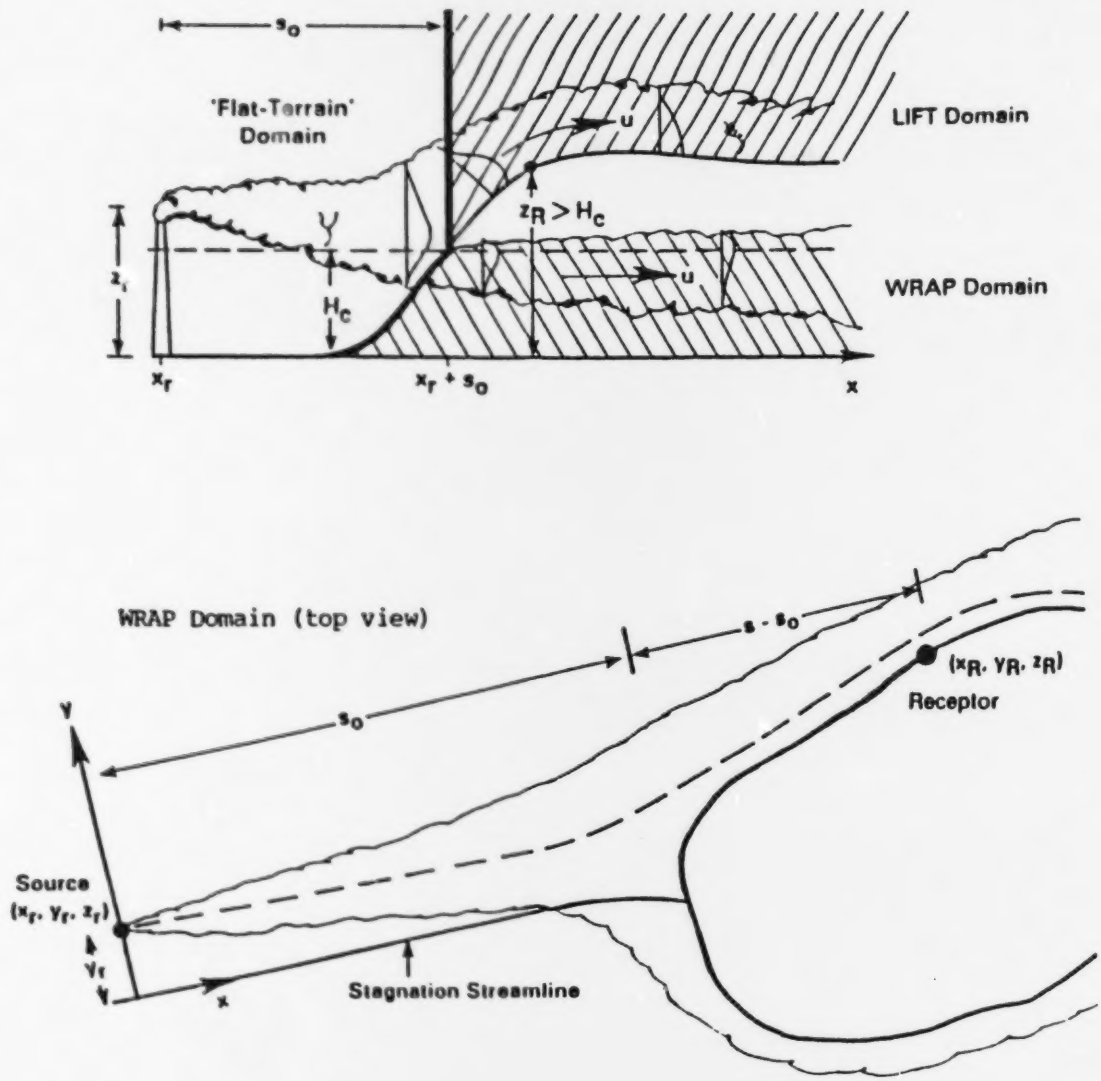
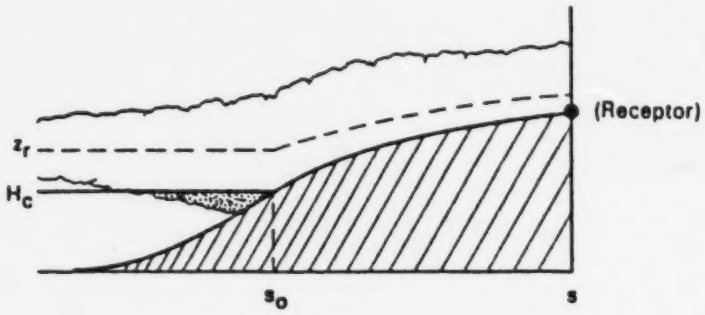
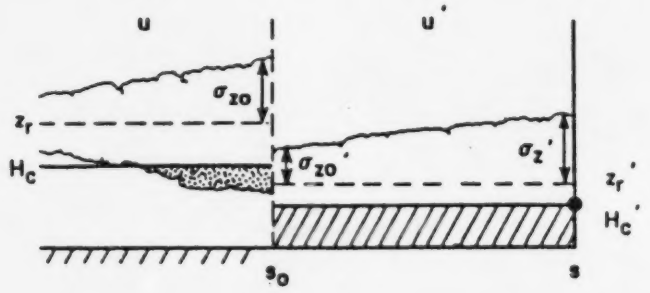


Figure 1. Idealized stratified flow about hills indicating the domain of individual CTDM component algorithms.

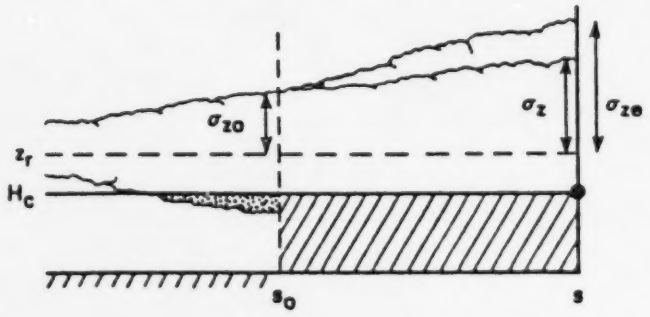


PHYSICAL PICTURE: material above H_c rides up and over hill in a distorted flow. Material below H_c passes round the side.



TERRAIN TREATMENT IN LIFT: terrain factors specify average terrain-induced flow modification from s_o to s (Equation 11).

$$z_r' - H_c' = T_h (z_r - H_c)$$
$$u' = T_u u$$
$$\sigma_{zo}' = T_h \sigma_{zo}$$
$$\sigma_z' = T_h \sigma_{ze}$$
$$\sigma_{ze}^2 = \sigma_{zo}^2 + (T_{\sigma z}^2 / T_h^2)(\sigma_z^2 - \sigma_{zo}^2)$$



LIFT CALCULATION: net effect of flow distortion is to increase the effective rate of plume growth (σ_{ze}) over that in the absence of the hill (σ_z)

Figure 2. Illustration of terrain effect on the vertical distribution of plume material above H_c as modeled in LIFT.

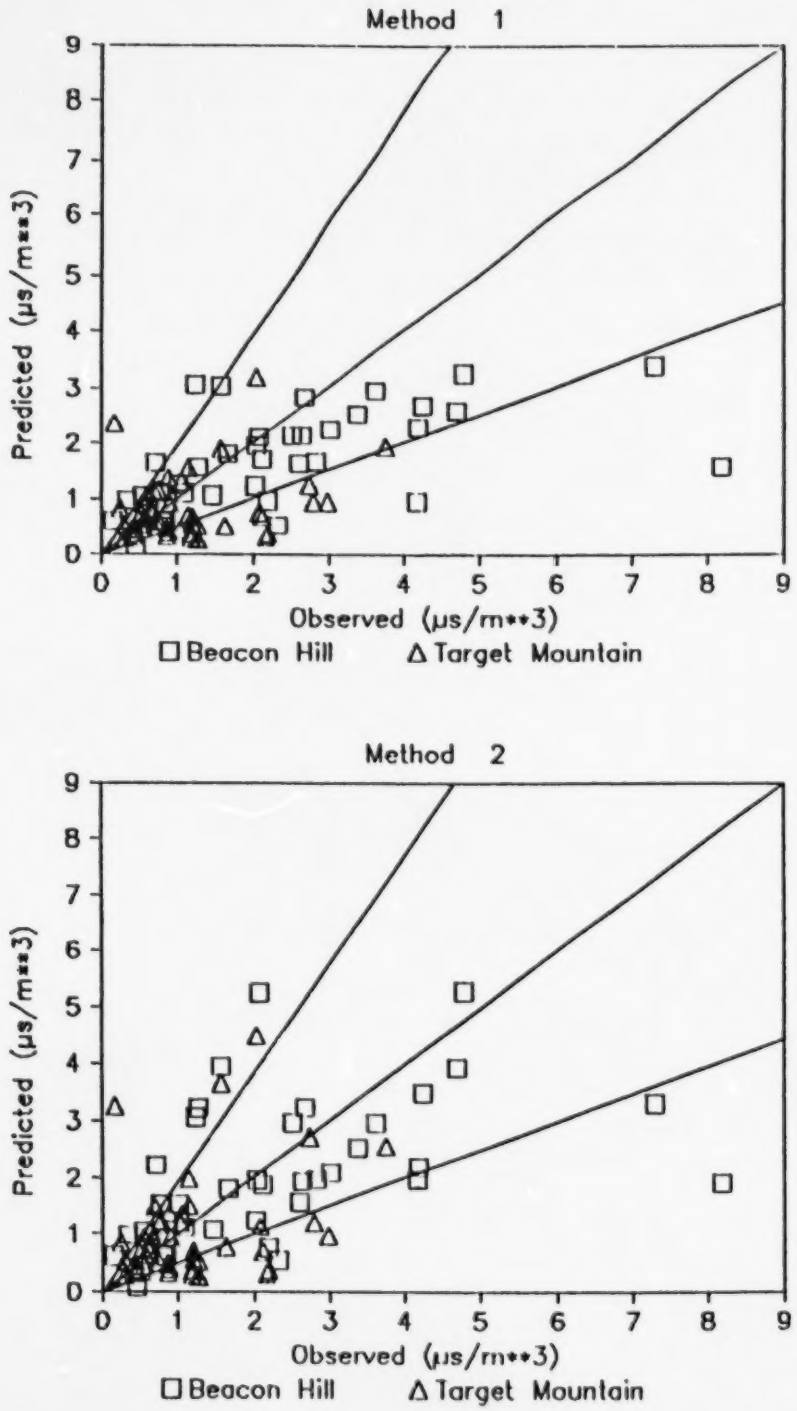


Figure 3. Scatterplots of predicted versus observed peak (average of the top 2) concentrations paired in time for Beacon Hill and Target Mountain. Method 2 differs from Method 1 in that the vertical turbulence is set to zero for hours in which the wind speed is less than 3 m/s.